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Health benefits of a reduction of PM_{10} and NO_2 exposure after implementing a clean air plan in the Agglomeration Lausanne-Morges

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ABSTRACT

Exposure to urban air pollution has been associated with adverse effects on cardio-vascular and respiratory health, both short and long term. Consequently, governments have applied policies to reduce air pollution. Quantitative health impact assessments of hypothetic changes in air pollution have been conducted at national and global level, but assessments of observed air pollution changes associated with specific clean air policies at a local or regional scale remain scarce. This study estimates health impacts attributable to a decrease in PM_{10} and NO_2 exposure in the Agglomeration of Lausanne-Morges (ALM), Switzerland, between 2005 and 2015, corresponding to the implementation period of a supra-municipal plan of measures to reduce air pollution in different sectors such as transport, energy, and industry (called Plan OPair 05). The health impact assessment compares health effects attributed to air pollution exposure levels in 2015 (reference case) with those in 2005 (counterfactual scenario), using 2015 as baseline for all other input data.

In the ALM, the modeled PM_{10} exposure reduction of 3.3 $\mu g/m^3$ from 2005 to 2015 prevents 26 premature deaths (equivalent to around 290 years of life lost), 215 hospitalization days due to cardio-vascular and respiratory diseases as well as approximately 47,000 restricted activity days annually. Monetized health impacts of the reduction of PM_{10} exposure are valued at approximately CHF 36 million annually. Immaterial costs, mainly related to the economic valuation of years of life lost, dominate the monetized health impacts (90% of total value), while savings at the workplace (net loss in production and reoccupation costs) amount to about CHF 1.9 million, and savings in health care costs to about CHF 0.5 million. The assessment is sensitive to the value assigned to immaterial costs and to uncertainties in the relative risk estimates, whereas variations in the baseline year (i.e. using 2005 data instead of 2015 data) affect results to a much lower degree. The alternative calculation based on NO_2 exposure, which dropped by 5.6 $\mu g/m^3$, suggests the prevention of 51 premature deaths (equivalent to around 550 years of life lost) overall impacts valued at CHF 49 million. All in all, the reduction in mortality due to the air quality improvements accounts for (depending on the considered pollutant) about 1% to 2% of total all-cause annual mortality in the ALM population or 4–8 times larger than the annual traffic fatalities in the ALM.

1. Introduction

Ambient air pollution is a well-known cause of a broad range of morbidities and premature mortality (Künzli et al., 2010; WHO, 2013a). Adverse health effects of poor air quality are of particular relevance in urban areas since density of both exposed populations and pollution sources is higher. To protect public health, WHO proposes science based guideline values as the target for clean air policies (WHO, 2005). Although very few countries adopted those values as national standards (Künzli et al., 2015) many governments worldwide have implemented clean air policies and strategies to successfully reduce ambient air pollution at different scales (Brauer et al., 2016).

For policy makers and the public it is of major relevance to understand the overall impact and costs of air pollution related health effects. In 1996, the Swiss Government was the first to ask scientists about the health impact and costs of traffic related air pollution in Switzerland (Künzli et al., 1997) neighboring France and Austria (Künzli et al., 2000). The methods developed for these studies were soon applied also on a global scale as part of the Global Burden of Disease (Cohen et al., 2005) and an increasing number

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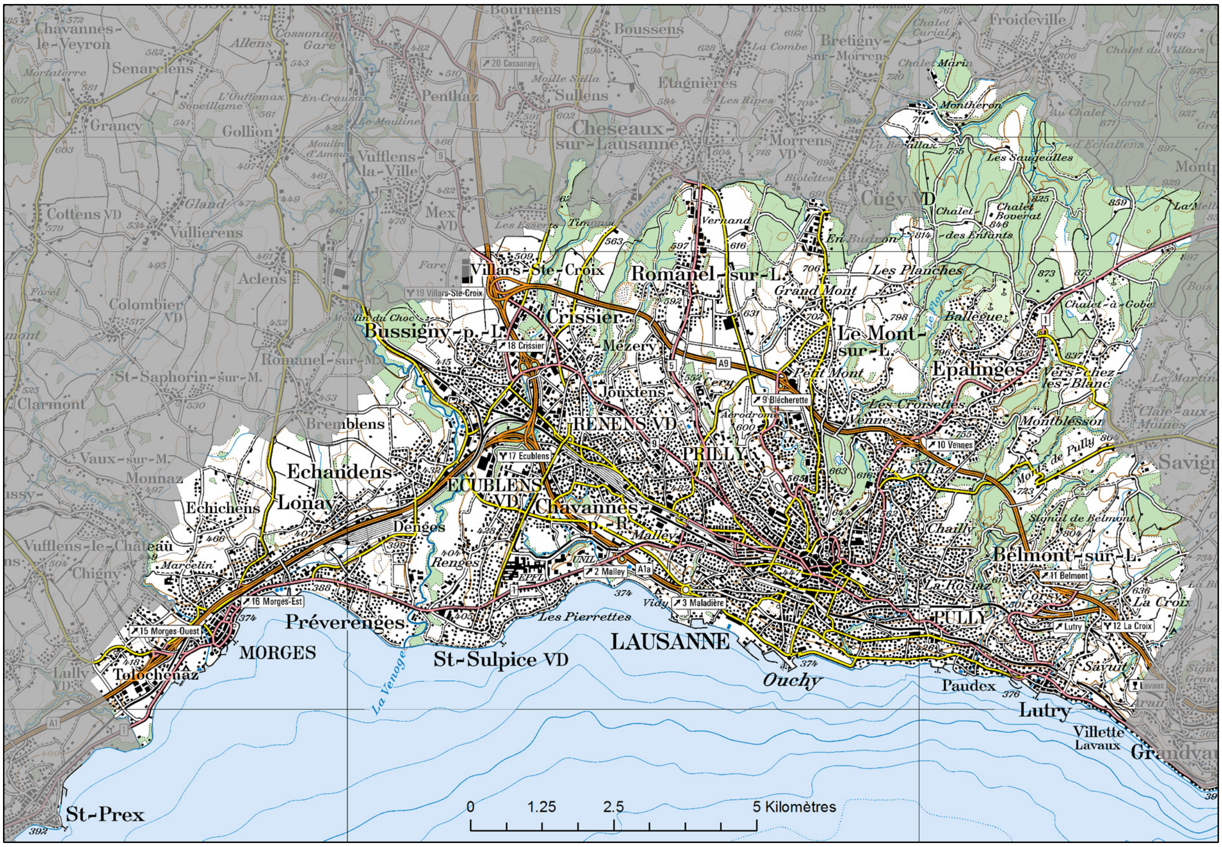

Fig. 1. ALM borders and municipalities involved in the application of the Plan OPair 05 (highways are represented in orange, major roads in yellow, green areas in green and the lake Geneva in blue) (Muller, 2016a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of studies have since then assessed air pollution impacts on the local, regional or national scale. Some responded to specific clean air policy scenario questions (e.g. Silveira et al., 2016) or city specific conditions (e.g. Ballester et al., 2008) or sources (e.g. Perez et al., 2013). The Swiss Government asked for repeated updates of these assessments with the last one referring to the air quality achieved in 2010 (ECOPLAN and INFRAS, 2014; Vienneau et al., 2015). Whereas national or international assessments are very useful in the national policy making discussions, those studies are less informative on the local scale of cities. However, cities are usually responsible for the local implementation of clean air policies, thus, may need to demonstrate the local health benefits of sometimes hotly debated local strategies.

The Ordinance on Air Pollution Control (OPair in French; *Ordonnance sur la Protection de l'AIR*) regulated in Switzerland in 1985 emissions, requirements of fuels, maximum permitted pollution levels and procedures in case of excessive levels (Swiss Federal Council, 1985). In the Agglomeration Lausanne-Morges (ALM), located in the Swiss Canton of Vaud, to apply the above mentioned national ordinance and to boost the reduction of air pollution initiated after previous municipal actions, the so called Plan of Measures OPair 2005 (from now on referred to as Plan OPair 05) was additionally implemented from 2005 to 2015 (Vaud, 2005). The Plan OPair 05 suggested fifty specific measures across different sectors such as mobility, transport of goods, energy production, industry and household energy consumption (Vaud, 2005) to reduce pollution in the 24 municipalities of the ALM (Fig. 1). The ALM had in 2015 around 293,000 inhabitants and a mortality rate of 337 deaths per 100,000 inhabitants (Table 1).

The goal of the present study, committed by the Canton of Vaud, was to estimate and monetize the health impacts associated with

Table 1
Key figures of the Agglomeration Lausanne-Morges.

Agglomeration Lausanne-Morges		
Feature	Value	Source
Number of municipalities	24	Vaud (2005)
Area	135 km^2	Muller (2016a)
Population in 2005	254,914 inhabitants	Oettli et al. (2016a)
Population in 2015	293,100 inhabitants	Oettli et al. (2016a)
All-cause mortality rate in 2015	739 deaths per 100,000 inhabitants	Oettli et al. (2016b)
Life expectancy at birth in 2012–2015	81 years for male, 85 for women	Oettli et al. (2016b)

the reduction of particular matter smaller than 10 μg (PM_{10}) and nitrogen dioxin (NO_2) exposure in the ALM from 2005 to 2015, i.e. the implementation phase of the Plan OPair 05. A sensitivity analysis was additionally performed regarding uncertainty in health effects, immaterial cost estimates, and choice of baseline year. To enhance comparability of the local ALM results with national assessments, methods were fully lined up with those used in the recent Swiss assessment (Vienneau et al., 2015). The specific steps of the calculations are described in the following sections. Methodology and results are explained in more detail in the Supplementary materials.

2. Materials and methods

2.1. General approach

As Fig. 2 shows air pollution decreased gradually in the ALM from 2005 to 2015 (Muller, 2016b). Applying a comparative risk

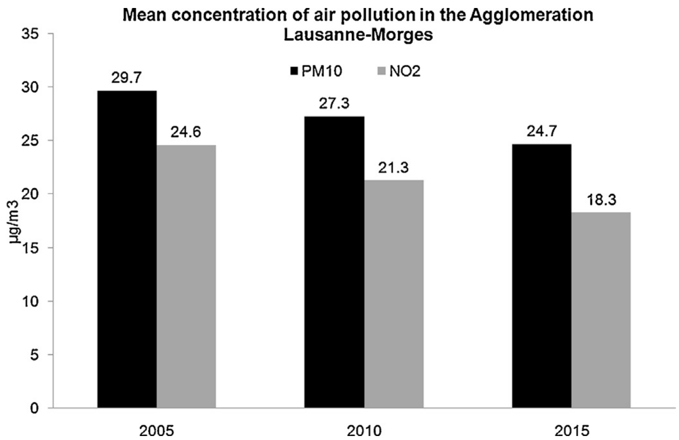

Fig. 2. Mean measured concentration of PM10 from three monitoring stations and NO2 from 150 passive sampler locations in ALM in 2005, 2010 and 2015 (NO2 measurements only available for these years between 2005 and 2015) (based on data from Muller, 2016b).

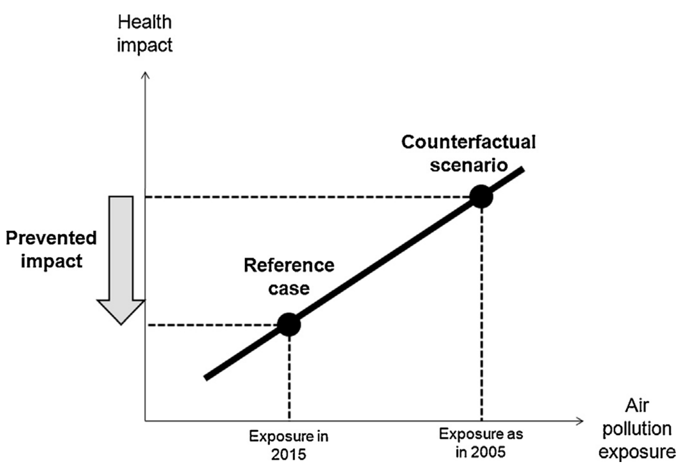

Fig. 3. Schematic representation of risk assessment comparing reference case and the counterfactual scenario.

assessment (WHO, 2016a), this study compares a reference case with an alternative – counterfactual – scenario (Fig. 3). The reference case is set in 2015 (end of the Plan OPair 05) using the actual status-quo in the ALM in terms of air pollution, population demographics, and disease rates. In contrast, the counterfactual scenario assumes that air pollution exposure did not change since 2005 (launch of the plan), i.e. uses exposure data from 2005, but otherwise uses the same population and health data from 2015 as the reference case. The associated health impacts were estimated as the difference between the impacts in the reference case and the counterfactual scenario. Thus, impacts are only calculated for one year, i.e. for 2015, what provides reasonable estimates also for the health impacts to be expected in the following years (assuming no changes in air pollution compared to 2015).

Fig. 4 shows a simplified workflow of the present study. Observed air pollution exposure levels, empirical relative risks, baseline health rates and population data were combined to estimate mortality and morbidity impacts. These impacts were monetized applying costs per health outcome unit.

Health outcomes considered were selected based on availability of concentration-response functions meta-analyzed from the peer-reviewed literature (Vienneau et al., 2015; WHO, 2013a) and included those listed in Table 2. Furthermore, all-cause (natural) mortality attributed to air pollution in post-neonatal (<1 years old) and adult population (≥30 years old) was estimated using three different measures; namely (all-age) premature deaths, years of life lost, and years of working life lost. Mortality impacts on people between 1 and 29 years old were not considered in this study due to the lack of epidemiologic evidence (key studies providing concentration-response functions did not included this age group).

The calculations were based on the methodology developed as part of the estimation of Swiss transport externalities (ECOPLAN and INFRAS, 2014) and expanded to include two markers of ambient air pollution, namely PM_{10} and NO_2 exposure, a strategy now approved by WHO (Héroux et al., 2015). The impacts of PM_{10} and NO_2 exposure are not intended to be aggregated, since these pollutants correlate in space and time, share a range of sources, and serve as partly overlapping markers of the same health effects (WHO, 2013a, p. 12WHO, 2013aWHO, 2013a, p. 12). Rather they serve as complementary estimates to gauge differences with regard to selected pollution indicators.

Details on the methods and all equations are provided in a Supplementary material.

2.2. Data

Exposure and population data from 2005 and 2015 for ALM were provided by the Canton of Vaud on a spatial resolution of 100 × 100 m (Muller, 2016c). PM_{10} exposure estimates were produced by a dispersion model that used the detailed emissions inventory of the Canton of Vaud (called CADERO) based on three monitoring stations, while NO_2 estimates were derived from approximately 150 measurement sites (passive sampling). The differences in population-weighted exposures between 2005 and 2015 were 3.3 $\mu g/m^3$ for PM_{10} and 5.6 $\mu g/m^3$ for NO_2.

The World Health Organization (WHO), as part of the project *Health Risks of Air Pollution In Europe* (HRAPIE), carried out a broad literature review and meta-analysis of international studies and air pollution epidemiology databases (APED) concerning the effects of PM, NO_2 and ozone (O_3), and provided recommendations on the corresponding relative risks for health impact assessments (WHO, 2013a). This study used relative risks recommended by WHO (2013a) and added an additional one from a meta-analysis of a more recent Swiss publication that provided the missing relative risk for asthma in adults (ECOPLAN and INFRAS, 2014). A log-linear concentration response relationship for both pollutants and all outcomes was assumed. Accordingly, relative risks were scaled to the local exposure applying a log-linear scaling function, thus, the percent increase per unit increase in pollution remains stable. Table 2 shows the list of relative risks and sources that were considered in this study.

Baseline mortality and morbidity rates used are presented in Table 3. Concerning mortality, two data sets were obtained for the ALM: (1) life tables (i.e. probability of dying) and (2) number of deaths by cause (i.e. natural and non-natural), both by one-year age group and gender. Probability of dying from all causes was derived from life tables for the period 2012–2015, while the share of natural deaths (i.e. excluding accidental and violent deaths) was based on averages from 2002 to 2014. Baseline morbidity rates were collected from several sources. Data on hospitalizations in 2015were provided by the Canton of Vaud and covered regions for medical statistics (MedStat), which slightly exceed the ALM area (Stadelmann, 2016a). For the remaining health outcomes, i.e. incidence and prevalence of bronchitis and asthma among children and adults as well as restricted activity days and working days lost, rates were adopted from Swiss and international studies previously used by Vienneau et al. (2015) and ECOPLAN & INFRAS (2014).

Population data as well as data regarding employed population in the ALM stratified by one-year age groups and gender were obtained from the Statistical Office of the Canton of Vaud (Oettli et al., 2016a). The data were aggregated as needed to match

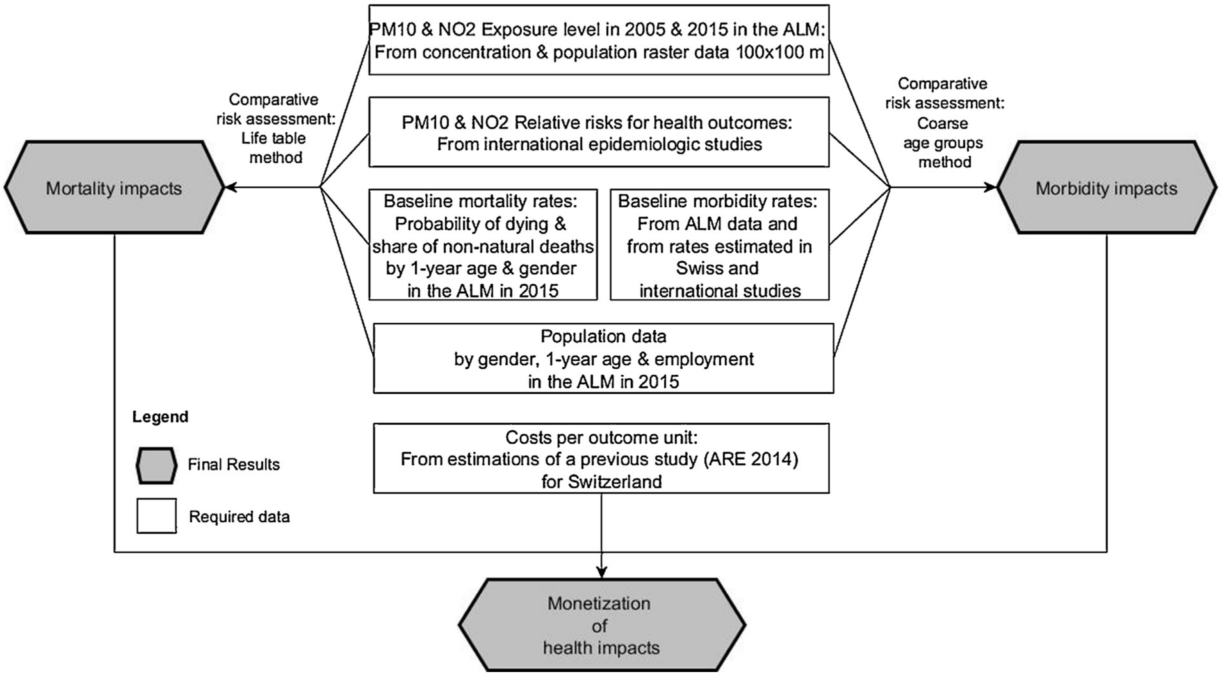

Fig. 4. Simplified workflow of the health impact calculation.

Table 2
Relative risk (RR) estimates and their 95% confidence interval (CI) as applied in the estimation of impacts.

		PM_{10}		NO_2	
Health outcome	Age group applied to	RR per 10 $\mu g/m^3$ (95% CI)	Source	RR per 10 $\mu g/m^3$ (95% CI)	Source
Mortality (all cause, natural)	≥30 Years old	1.045 (1.029–1.060)[f]	WHO (2013a) based on a meta-analysis of 13 studies from Hoek et al. (2013)	1.055 (1.031–1.080)	WHO (2013a) based on a meta-analysis of 11 studies from Hoek et al. (2013)
Post-neonatal infant mortality (all cause, natural)	0–1 Years old	1.040 (1.020–1.070)	WHO (2013a) based on Woodruff et al. (1997)		
Hospital admissions for CVD (including stroke)	All ages	1.007 (1.001–1.012)[f]	WHO (2013a) based on own APED meta-analysis of 5 studies		
Hospital admissions for RD	All ages	1.014 (0.999–1.029)[f]	WHO (2013a) based on own APED meta-analysis of 3 studies	1.018 (1.012–1.025)	WHO (2013a) based on own APED meta-analysis of 15 studies
Incidence of chronic bronchitis in adults	≥18 Years old	1.117 (1.040–1.189)	WHO (2013a) based on a combination of 2 studies		
Prevalence of bronchitis in children	5–17 Years old [a]	1.080 (0.980–1.190)	WHO (2013a) based on Hoek et al. (2012)		
Asthma attacks in adults with asthma	≥18 Years old [b]	1.029 (1.013–1.045)	Vienneau et al. (2015) based on a meta-analysis of 6 studies carried out by ARE (2004)		
Days with asthma symptoms in asthmatic children	5–17 Years old [c]	1.028 (1.006–1.051)	WHO (2013a) based on a meta-analysis of 36 studies from Weinmayr et al. (2010)		
Restricted activity days	≥18 Years old [d]	1.034 (1.030, 1.038)[f]	WHO(2013a) based on Ostro (1987)		
Work days lost	>15 Years old (employed persons)[e]	1.033 (1.028, 1.038)[f]	WHO(2013a) based on Ostro (1987)		

[a] Original age group of the PM_{10} relative risk: 6–12 (now applied to 5–17).
[b] Original age group of the PM_{10} relative risk: >14 (now applied to 5–17).
[c] Original age group of the PM_{10} relative risk: 5–19 (now applied to 5–17).
[d] Original age group of the PM_{10} relative risk: all ages (now applied to ≥18).
[e] Original age group of the PM_{10} relative risk:20–65 (now applied to >15).
[f] The original relative risk was converted from $PM_{2.5}$ to PM_{10} using a log-linear conversion function.

Table 3
Baseline health rates applied in the estimation of impacts.

Health outcome	Age group	Baseline health rates for general population	Source
Mortality (all cause, natural)	≥30 Years old	Probability of dying by one-year age group and gender extracted from the life table for the period 2012–2015 in the ALM; share of non-natural deaths by one-year age group and gender for the period 2002–2014 in the ALM	Dataset on vital statistics from the Statistical Office of the Canton of Vaud (Oettli et al., 2016b)
Post-neonatal infant mortality (all cause, natural)	<1 Year old	Probability of dying by one-year age group and gender extracted from the life table for the period 2012–2015 in the ALM MedStat regions	Dataset on vital statistics from the Statistical Office of the Canton of Vaud (Oettli et al., 2016b)
Hospital admissions for CVD (including stroke)	All ages	1.21 admissions and 16.46 days of hospitalization per 100 inhabitants in 2015 in the ALM MedStat regions (data from patients living in the ALM Med-Stat regions that are treated in hospitals of the Canton of Vaud)	ICD-10 I00-I99 hospitalization data collected by the Swiss Federal Statistical Office and provided by the Statistical Office of Canton of Vaud (Stadelmann, 2016b)
Hospital admissions for RD	All ages	1.00 admission and 7.40 days of hospitalization per 100 inhabitants in 2015 in the ALM MedStat regions (data from patients living in the ALM Med-Stat regions that are treated in hospitals of the Canton of Vaud)	ICD-10 J00-J99 hospitalizations from the database of the Statistical Office of Canton of Vaud (Stadelmann, 2016b)
Incidence of chronic bronchitis in adults	≥18 Years old	0.39 cases per 100 adults and year	Vienneau et al. (2015) based on Swiss study SAPALDIA (Schindler et al., 2009)
Prevalence of bronchitis in children	5–17 Years old [a]	18.6 cases per 100 children and year	Vienneau et al. (2015) based on the PATY study in six countries including Switzerland (Hoek et al., 2012)
Asthma attacks in adults with asthma	≥18 Years old	21 attacks per 100 adults and year (based on 3.9 yearly asthma attacks per asthmatic adult and 5.4 asthmatics per inhabitant)	ECOPLAN & INFRAS (2014) based on the European Community Respiratory Health Survey (Burney et al., 1996)
Days with asthma symptoms in asthmatic children	5–17 Years old [b]	304 symptom days per 100 children and year (based on prevalence of 4.9% of severe asthma in children and daily incidence of 17% of symptoms in children with asthma)	Vienneau et al. (2015) based on the international study ISAAC (Lai et al., 2009)
Restricted activity days	≥18 Years old	1900 days per 100 adults per year	Vienneau et al. (2015) based on Ostro (1987)
Working days lost	≥15 Years old (employed persons)	720 days per 100 employed persons and year	ECOPLAN & INFRAS (2014) based on HEIMTSA (2010)

[a] The original source refers to children at the age group 6–18 (now applied to 5–17).
[b] The original source refers to children at the age group 5–19 (now applied to 5–17).

the corresponding age groups used for the morbidity and some mortality-related calculations (see age groups in Table 3). Population data were from 2015, while employment figures were averages for the period 2010–2014.

Costs per outcome unit were used from a previous study, which was committed by the Federal Office of Spatial Planning (ARE in German) and estimated external costs of transport in Switzerland (ECOPLAN and INFRAS, 2014; pp. 140–148). Figures from 2010 were adjusted to 2015 applying the average inflation rate in Switzerland in this period (−2.7% since 2005; −2.5% for health care costs) (FSO, 2016).

2.3. Estimation of health impacts

Impacts of air pollution were quantified by calculating population attributable fractions (PAF), which quantify the fraction of all cases of a specific outcome that can be attributed to a certain exposure – in this case air pollution (Zapata-Diomedi et al., 2016). PAF is a function of the relative risk and the population at risk. This study assumes that 100% of the population is exposed population. Health impact assessment estimates PAFs based on the air pollution levels of the reference and the counterfactual scenario and quantifies the difference in attributable cases. Separate PAFs were calculated for the strata defined by outcome (mortality and various morbidities), pollutant (PM_{10} or NO_2), pollution level (reference or counterfactual), and age groups. These PAFs were applied to the outcome calculations based on population and background health data.

Mortality impacts were estimated applying a life table method (Miller and Hurley, 2003; Röösli et al., 2005) following ECOPLAN & INFRAS (2014) and Vienneau et al. (2015). Life tables allow accurate calculations of years of life lost by taking into account the different life expectancies at different ages, e.g. 81 years among men and 85 years among women born in the ALM in 2012–2015 (Oettli et al., 2016b). Probability of dying due to natural causes was calculated by age-year and for each year from 2015 till one hundred years into the future, based on current population and mortality data. Based on this, years of life lost due to natural causes were quantified. Under

Table 4
Annual prevented health impacts due to the reduction of exposure to PM_{10} and NO_2 in the ALM from 2005 to 2015.

Health outcome	PM_{10}	NO_2	Unit
Premature deaths[a]	26	51[c,d]	Deaths
Years of life lost (<1 & ≥30 years old)[a]	289	546[c,d]	Years of life
Years of working life lost (<1 & ≥30 years old)[a]	34	55[c,d]	Years of working life
Hospitalization days due to CVD (all ages)	103		Hospitalization days
Hospitalization days due to RD (all ages)	112	244[d]	Hospitalization days
Incidence of chronic bronchitis in adults (≥18 years old)	27		Cases
Prevalence of bronchitis in children (5–17 years old)	149		Cases
Asthma attacks in adults with asthma (≥18 years old)	447		Attacks
Days with asthma symptoms in asthmatic children (5–17 years old)	970		Symptom days
Restricted activity days (≥18 years old)[b]	46,903		Days
Working days lost (≥15 years old, employed persons)[b]	10,986		Days

[a] Premature deaths, years of life lost and years of working of life lost are overlapping indicators and therefore non-additive with each other when monetizing, i.e. only one of the monetized impacts should be considered depending on the cost category of interest (see Table 5).
[b] Restricted activity days and working days lost are overlapping indicators and therefore non-additive with each other when monetizing, i.e. only one of the monetized impacts should be considered depending on the cost category of interest (see Table 5).
[c] Not including infants (i.e. persons aged <1 years old) due to lack of applicable relative risk.
[d] PM_{10} and NO_2 health impacts should not be aggregated since they might overlap (see General Approach in Section Materials and Methods).

the reference case, these were multiplied by the PAF for air pollution levels in 2015 to derive years of life lost attributable to 2015 air pollution levels. Under the counterfactual scenario, the same was done with the PAF for air pollution levels in 2005. Annual years of life lost attributable to the reduction in air pollution between 2005 and 2015 are the difference in years of life lost attributable to air pollution 2015 and 2005. Attributable years of life lost were aggregated for ages 30 and older, and postnatal deaths. Years of working life lost were calculated by applying the share of employed population to ages 15 and older (including employed population above usual retirement age, i.e. 65 for men and 64 for women). This again was done by one-year age group and year (from 2015 till one hundred years into the future) to the previously obtained years of life lost.

Morbidity impacts attributable to air pollution were calculated following the same approach, applying PAFs to baseline disease rates for the reference and counterfactual scenario, and then calculating the difference in attributable cases.

2.4. Monetization

Costs were classified into four categories, namely medical costs (costs for hospital treatments of air pollution related diseases), net loss in production (cost for employers when reducing yields due to absenteeism among air pollution exposed employees), reoccupation costs (costs for employers replacing employees due to health impacts of air pollution) and immaterial costs. Immaterial costs are based on Value of a Statistical Life (VSL), which represents the value a given population places ex ante on avoiding the death of an unidentified individual (OECD, 2012). VSL is based on studies that request individual's willingness to pay for small reductions in mortality risk, which are then extrapolated to reflect the value of reducing risk to save one life. Conceptually, willingness to pay also includes the share of health costs paid directly by the victims and lost consumption, in addition to immaterial costs (ECOPLAN and INFRAS, 2014; p. 141). This study used a VSL value of CHF 3.3 million updating the value of a previous national Swiss report on external effects of transport (ECOPLAN and INFRAS, 2014; p. 146).

In order to monetize health impacts, costs per health outcome unit were multiplied by the estimated number of corresponding outcomes. When assessing total costs, not all outcomes must be added up to avoid double counting of impacts for which there are more than one overlapping indicator. Therefore, this study only monetized one outcome per cost category (i.e. immaterial costs of years of life lost were considered but not of premature deaths; production costs of years of working life lost were considered but not all years of life lost; immaterial costs of restricted activity days were considered but no production costs of working days lost; see Table 5). Costs due to hospitalizations as well as asthma and bronchitis were subtracted from costs attributed to restricted activity days and working days lost.

The value of future years of life was discounted according to economic approaches suggesting that future values are worth less than present values. An annual discount rate of 2% and growth rate of 1% was applied according to the Swiss Norm for Cost-benefit Analysis in Road Transport (*SN 641 821*).

2.5. Sensitivity analysis

A sensitivity analysis was carried out to assess the influence of two key input data: (a) relative risks and (b) immaterial cost value applied to health outcomes. For relative risks, lower and upper bounds of the 95% confidence intervals were used (WHO, 2013a), while for immaterial relative cost of health outcomes values 50% lower and 100% higher were applied following ARE (2004, p. 75). Additionally, the baseline year for the reference case and counterfactual scenario was shifted from 2015 to 2005 to assess the sensitivity of results towards changes in population and baseline health data.

3. Results

3.1. Health impacts

Table 4 shows the estimated health impacts for one year (2015) that were prevented in the ALM as a result of the reduction in air pollution exposure of 3.3 $\mu g/m^3$ PM_{10} and 5.6 $\mu g/m^3$ NO_2, within the period of the Plan OPair 05, i.e. 2005–2015. According to this estimation, the reduction of exposure to PM_{10} prevented 26 premature deaths (equivalent to around 290 years of life lost including 30 years of working life lost) among infants below 1 year old and adults age 30 and older. Furthermore, approximately 100 hospitalization days due to CVD and 110 due to RD, respectively, 30 incident cases of bronchitis and 450 asthma attacks in adults and about 150 prevalent cases of bronchitis and 1,000 asthma symptom days in children were prevented. Finally, around 47,000 restricted activity days were prevented, including around 11,000 working days lost.

Assessments based on NO_2 resulted in approximately two times larger attributable burdens (years of life lost, years of working life lost and hospitalization days due to RD). NO_2 mortality outcomes do not include infants younger than one year old because no applicable relative risk for all cause mortality was available.

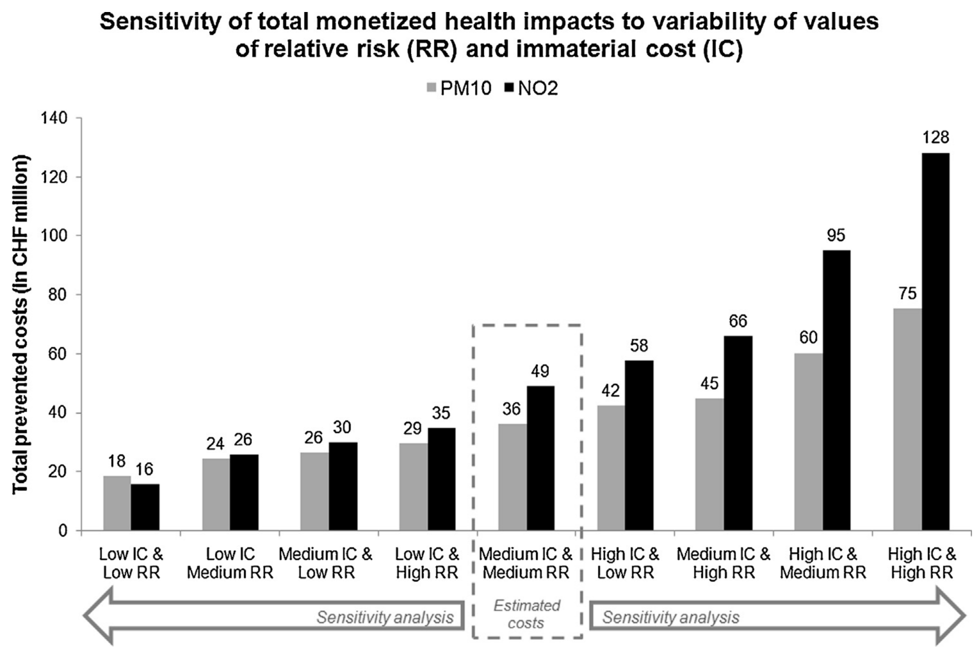

Fig. 5. Sensitivity analyses of total prevented costs for the reduction of PM_{10} and NO_2 exposure in the ALM from 2005 to 2015 when varying relative risks (RRs) between low and high 95% confidence interval values and immaterial costs between low and high estimates.

3.2. Monetized value of health impacts

The result of monetizing the above health impacts are shown in Table 5. The reduction in air pollution between 2005 and 2015 results in annual benefits valued at CHF 36 million (PM_{10}) to CHF 49 million (NO_2) in the ALM. Immaterial costs make up for 94% of these benefits (CHF 34 and 46 million for PM_{10} and NO_2, respectively). Medical cost savings amount to around CHF 0.5 million for PM_{10} or CHF 0.2 million for NO_2. Work-related cost savings (net loss in production and reoccupation costs) are in the range of CHF 1.9 millions for PM_{10} or CHF 2.5 million for NO_2. Premature deaths were not monetized because they are contained in the years of life lost. Net loss in production was estimated using working days lost, while immaterial costs were estimated using restricted activity days to avoid double counting of overlapping indicators (see Materials and Methods and Table 4).

3.3. Sensitivity analysis

The sensitivity of monetized health impact estimations to variability of relative risks and immaterial cost was analyzed (Fig. 5). In the calculations based on the lower bound (95% CI value of relative risks and the low immaterial cost estimate per outcome unit) total prevented costs of reducing pollution in the ALM from 2005 to 2015 were around CHF 18 million in terms of PM_{10} exposure or CHF 16 million in terms of NO_2 exposure. Using instead the higher bound (CI value of relative risks and high immaterial cost estimates), prevented costs reach CHF 75 million when considering PM_{10} difference of exposure or CHF 128 million when considering NO_2. When exclusively varying relative risk values (fixed medium value of immaterial cost) in PM_{10} exposure, total prevented costs range from about CHF 26 million (27% lower than the medium bound) to about CHF 45 million (24% higher). In contrast, when varying immaterial cost per health outcome unit and fixing relative risk, total prevented cost of the reduction of PM_{10} exposure range from about CHF 24 million (33% lower) to CHF 60 million (66% higher).

When using population and baseline health data from 2005 instead of 2015, the estimation of mortality impacts in terms of prevented years of life lost and years of working life lost is 1% and 5% higher respectively, while the number of prevented premature deaths is 1% lower.

4. Discussion

This study has found that in the ALM the prevention of 26 premature deaths per year can be attributed to the reduction of PM_{10} exposure by 3.3 $\mu g/m^3$, as achieved during the 10-year period of the Plan Opair 05 (i.e. from 2005 to 2015). The estimates based on NO_2 exposure, which was reduced by 5.6 $\mu g/m^3$ since 2005, are about twice as high. The reduction in premature deaths due to these air quality improvements is equivalent to about 1% to 2% of the total all-cause annual mortality in the ALM and about 4–8 times larger than all annual traffic fatalities in the ALM (Martin and Oettli, 2016). Moreover, the reduction of years of life lost is equivalent to about 5% to 10% of years of life lost of ALM population younger than 70 years old (assuming that this is the average life expectancy of all-age ALM population within the period 2005–2015) (Pasche and Oettli, 2016). The value of health impacts prevented every year amounts to CHF 36 million and CHF 49 million, or about CHF 120 to CHF 170 per ALM inhabitant, for PM_{10} or NO_2, respectively. These findings are somewhat sensitive with regards to uncertainty in relative risks (−24% to +27%) and the value assigned to immaterial costs (−33% to +66%). Choice of baseline year (2005 instead of 2015) for population and health data had little influence on the results.

This is one of only few studies that valued health impacts of specific clean air policies on such local level. For instance, Künzli et al. (2000) attributed 6% of total mortality in Switzerland (around 8 million inhabitants) for a counterfactual air pollution contrast of 14 $\mu g/m^3$ PM_{10}. In a more recent assessment in Switzerland Vienneau et al. (2015) attributed 14,000 years of life lost and 8,700 hospital days due to CVD every year to air pollution from transport alone (contrast of 19.4 $\mu g/m^3$ PM_{10}). For the metropolitan area of Barcelona with about 3.8 million inhabitants, about ten times more than in the ALM, Perez et al. (2008) estimated that reducing PM_{10} concentrations by 30 $\mu g/m^3$ would prevent 3,500 deaths and 1,800 CVD hospitalizations annually. The recently completed ESCAPE project (Beelen et al., 2014) has confirmed, for the first time

Table 5
Monetization (in CHF millions) of medical costs (MC), net losses in production (NLP), reoccupation costs (RC) and immaterial costs (IC) of health impacts attributed to the reduction in air pollution (2005–2015).

Cost saving (in CHF million)	PM_{10}					NO_2				
Health outcome (applied age group)	MC	NLP	RC	IC	Total	MC	NLP	RC	IC	Total
Years of life lost (<1 & ≥30 years old, discounted)				24.058	24.058				46.000	46.000
Years of working life lost (<1 & ≥30 years old, discounted)		0.426	1.023		1.448		0.729	1.751		2.480
Hospitalization days due to CVD (all ages)	0.153	0.006		0.081	0.240					
Hospitalization days due to RD (all ages)	0.112	0.008		0.088	0.208	0.245	0.017		0.191	0.453
Incidence of chronic bronchitis in adults (≥18 years old)	0.180	0.006		2.901	3.087					
Prevalence of bronchitis in children (5–17 years old)	0.008	0.000		0.043	0.052					
Asthma attacks in adults with asthma (≥18 years old)	0.000	0.007		0.031	0.038					
Days with asthma symptoms in asthmatic children (5–17 years old)	0.001	0.003		0.067	0.070					
Restricted activity days (≥18 years old)				6.595 [a]	6.595					
Working days lost (≥15 years old, employed persons)		0.401 [a]			0.401					
Total	0.454	0.856	1.023	33.866	36.198	0.245	0.746	1.751	46.191	48.933

[a] Costs for hospitalization, bronchitis and asthma have been subtracted from restricted activity days and work days lost.

in Europe, that there is no lower "threshold of no effect" of ambient air pollution on mortality, providing a clear rationale to further improve air quality, and to quantify the benefits of such improvements, even at relatively low levels of pollution, as seen in the ALM. Swiss data also contributed to ESCAPE. Given this evidence, further reductions of air pollution will continue to result in the same additional and sustainable benefits – every year.

This study relies on several assumptions and has some limitations (explained below) that should be taken into account when interpreting the results.

The study considers two air pollution indicators, PM_{10} and NO_2. PM_{10} is generally considered an indicator of background and secondary pollution originated from both local and remote sources (Perez et al., 2008; Wang et al., 2006). Thus, spatial variation is rather limited and reliable estimates of exposure can be derived from a few stations, such as the three monitors used to inform the ALM model. Local policies may have only limited effects on PM_{10} given the long-range transboundary travel of these pollutants. NO_2 concentrations, on the other hand, are less homogeneously distributed in space. If measured at many sites, as done in the ALM, NO_2 more accurately captures variations in local combustion sources, such as traffic, which is a primary target of the measure of the Plan Opair 05. When assessing the impacts of local policies, the use of a traffic-sensitive pollution indicator, like NO_2, is therefore particularly appealing. In its aim to provide a comprehensive assessment of health impacts of air pollution reductions, this study therefore used both, PM_{10} and NO_2 as complementary indicators. This implies, however, that where available for the same outcome, impacts should not be added up, as they may largely overlap. To date, so called 2-pollutant models are inconclusive with regards to quantifying the independent effects of each marker of pollution, and the degree of overlap of correlated indicators (WHO, 2013a, 2014a). However, the epidemiologic literature on health effects of NO_2 is still less exhaustive, lacking risk estimations for several outcomes that have been associated with particulate matter (see Table 2). Moreover, to guarantee comparability with the last estimation of Swiss transport externalities (ECOPLAN and INFRAS, 2014), this study also abstained from adding outcomes not previously considered in PM based assessments. For instance, we have not added asthma onset as a consequence of exposure to NO_2 although a recent study provided meta-analytic evidence for this outcome (Khreis et al., 2017). Thus, the overall impact of the NO_2-based assessment covers only a subset of the PM-related impact.

The substantially higher impacts for NO_2 – among outcomes assessed for both markers – probably reflect either a chance finding (given the substantial overlap in the ranges of uncertainties) or a combination of the more pronounced relative reduction in NO_2 concentrations (presumably as a result of targeted OPair 05 policies) and/or stronger toxicological effects associated with NO_2 or its correlates, namely traffic exhaust. Additionally, uncertainties in exposure assessment both in the local air pollution model, as well as in the underlying epidemiologic studies may have contributed to the differences between the two pollution indicators. It should also be noted that total impacts for NO_2 would have been even higher if additional relative risks would be available. Future NO_2 based risk assessments may include other health outcomes.

This assessment did not include O_3 and SO_2 although it is well known that ambient exposure to pollutants marked with these gases causes additional health problems (WHO, 2013a; Nafstad et al., 2003) that occur independently of those attributed to PM or NO_2. A report of the U.S. Academies of Sciences agreed with impact assessment strategies that add O_3 impacts to those quantified for PM (NRC, 2008) and indeed, the Global Burden of Disease studies (Brauer et al., 2016) provide estimates for both, $PM_{2.5}$ and O_3. However, as compared to the overall effects associated with PM, the O_3 associated burden is negligible, particularly in cities where O_3 levels tend to be lower due to the scavenging of O_3 by primary pollutants such as traffic emissions. Moreover, although O_3 concentrations showed downward trends in Switzerland, these changes were less strong and more relevant in rural areas. O_3 is also a regional phenomenon, thus, local policies such as those implemented by the Plan OPair 05 have only a limited impact on O_3 in the ALM. Furthermore, it could be of interest to use $PM_{2.5}$ as an alternative measure. However, such concentration data are currently not available for the ALM. Neglecting SO_2 related effects is also expected to be irrelevant in this Swiss study given that SO_2 concentrations got reduced to very low levels until the end of the last century, thus, changes during the last decade were very minor (INFRAS and Meteotest, 2013).

All concentration-response functions used in this assessment rely on multivariate adjusted estimations of the contribution of air pollution to the various outcomes. However, the relative risk estimates used in this assessment still have different levels of uncertainty, as emphasized in the investigations and guidelines of the WHO projects REVIHAP (WHO, 2013b) and HRAPIE (WHO, 2013a). For example, there is a very strong and broad evidence for air pollution effects on mortality and life expectancy, including meta-analytic effects (i.e. relative risks) partly based on Swiss data (Beelen et al., 2014). In contrast, estimates for restricted activity days are based on only a few older U.S.-based studies (Ostro, 1987). It is worth noting, though, that the overall impacts are substantially driven by effects on mortality, thus the most reliable health effect estimates. Nonetheless, a recent study adopting different causal modeling approaches suggests that the currently used relative risks may underestimate the air pollution risk for mortality, reporting much larger effects on loss in life expectancy (Schwartz, 2016). Further, the health outcomes assessed in this study are based on research published in the past years, whereas most recent findings are not yet considered. For example, evidence of a causal role of air pollution in the development of metabolic syndrome (Eze et al., 2015) and diabetes is not only supported by the Swiss SAPALDIA study (Eze et al., 2014) but also confirmed by a systematic review and meta-analysis (Eze et al., 2015) or the above mentioned review on asthma onset in relation to air pollution. These and other health outcomes have not been considered in the assessment of this study, which, thus, must be interpreted a conservative quantification of only the minimal benefits of the Plan OPair 05. Our primary reason to not expand the assessment was the importance and relevance for the local authorities to keep this assessment fully comparable with the recent Swiss National assessment (ECOPLAN and INFRAS, 2014).

This study applies three different types of monetization including medical costs, production costs, and immaterial costs. Although in theory these are additive, it is important to keep in mind that immaterial costs are very different in nature compared e.g. to health care costs based on actual hospital spending. Furthermore, immaterial costs dominate the total prevented costs, and thus the value assigned to immaterial costs is very influential. Variation in VSL is considerable across studies and populations (OECD, 2012). The VSL value of CHF 3.3 million used here is the same as in ECOPLAN and INFRAS (2014). This value is considerably lower than that suggested by a major meta-analysis conducted by OECD (2012). According to the WHO's Health Economic Assessment Tools (HEAT) for walking and cycling, this would put the VSL for Switzerland at CHF 8.9 million, after adjustment for purchasing power (WHO, 2016b).

Concerning the interpretation of the findings of this study it should be noted that the health impacts estimations are attributable to the reduction of air pollution from 2005 to 2015. However, to what extent these reductions could be attributed to the Plan OPair 05 alone remains unknown and was outside of the scope of this work. Additional local and regional factors not affected by the Plan OPair 05 may have contributed to changes in air quality as well. Second, ALM air quality may also have benefited from the adoption of clean air policies in neighboring cities, counties and indeed in Europe, such as major reductions of exhaust-related pollutants due to revised European emission standards (Euro V). Moreover, to comprehensively assess impacts attributable to Plan OPair 05 per se, one would need to consider its beneficial effects on air quality in the region at large, and the lag in effects of policies, which may yet to result in further reductions in air pollution. It should also be emphasized that the reference year (2005) does not indicated the beginning of clean air policies in the ALM. Indeed, air quality was much worse in the 1980s and 1990s and the related benefits are all due to local, national, and international clean air policies.

This study points to a number of ways in which future research may contribute to the improvement of similar health impact assessments, as discussed below.

Robust assessments of the effectiveness of specific clean air policies in terms of their effects on emissions and ambient concentrations remain a key research need to inform future policy making locally and nationally or internationally. Intermediate factors, such as changes in vehicle fleet and travel behavior may serve as proxies for such evaluations.

To better understand and judge the value of clean air – and other – policies it is desirable to expand the scope of health impact studies to include other risk factors and physiological pathways. A textbook example are transport policies aiming to shift car trips towards more sustainable modes of transport, which can improve public health not only in terms of improvements of air quality but simultaneously by increasing physical activity, and reducing injury risks or exposure to noise (Mueller et al., 2017; Schepers, 2012). Such assessments will provide an excellent basis for the evidence based allocation of public resources and for maximizing synergies between possibly interrelated policies. For example, speed reductions of traffic may reduce air pollution, noise, and accidents.

Further insights could be gained from direct comparisons of health impact assessments between related or even competing policy frameworks, possibly including cost-effectiveness analyses (Brown et al., 2016; Cecchini et al., 2010; Tengs et al., 1995). However, challenges of harmonizing assessment methods, data, and in particular cost estimates for policies across domains as diverse as occupational hazards, public smoking policies, traffic safety or urban planning remain substantial.

Finally, the development of user-friendly tools for health impact assessment, similar to for instance HEAT with regards to active mobility (WHO, 2014b), could be considered to facilitate more routine-uptake of quantitative health impact assessments to inform policy-making.

5. Conclusions

The health impacts attributable to a reported reduction of air pollution from 2005 to 2015 were estimated and monetized at the regional scale of the ALM. Considering various assumptions and limitations of this assessment, and given the continued increase in evidence revealing additional adverse effects of air pollution, the results of this study are likely reflecting a conservative underestimation of the total benefits attributable to the improvement of air quality seen in the ALM during the implementation of the Plan OPair 05.

While the assessment based on PM_{10} allowed including a broader range of health outcomes, overall impacts based on NO_2 were considerably larger, possibly capturing more specifically the impact of the Plan OPair 05 on local transport related emissions whereas improvements in PM_{10} are more substantially a consequence of regional and national policies.

Assessments of health impacts as the one carried out in the present study help informing decision makers in public administrations to evaluate or predict the success of concrete regional clean air policy such as the Plan OPair 05. Future efforts should aim at widening the scope of such assessments in terms of considered health pathways and related policies. The applied methodology could also be integrated in user-friendly tools that facilitate routine applications.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ijheh.2017.03.012.

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